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International radar networking
Sea-breeze front on radar
Cloud-head image

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International radar networking

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I am going to talk about International Radar Networking, the COST-73 project, which ran from 1986 to 1991. I was Chairman of the Management Committee responsible for organizing parcels of work. I notice Colin Fair at the back and he takes a lot of responsibility for much of the work that was actually done by the United Kingdom. What I want to do is to outline the programme for this research project, and then give illustrations of some the work that has actually been undertaken. Before I do that I will begin by explaining what the COST programme is, because some of you may not be familiar with it.

COST is a European Commission programme Co-Operation in Science and Technology, and it was a programme established in 1970. In fact we also celebrated, in November 1991, the joining to that programme of some Eastern European countries. Many subjects other than meteorology, for example materials and social sciences, are all part of the COST programme. Meteorology was included from the beginning. Indeed, perhaps the greatest achievement of COST (you possibly might not be aware) was that it led directly to the formation of the European Centre for Medium-range Weather Forecasts from COST-70. It has had some further successes. You can judge whether it has led to improvements in the surface observational database in part from what I am going to say. However, the programme has also been concerned with buoys, with radiosondes, and now wind profilers. The United Kingdom have the Vice Chairmanship of COST-74, the wind profiler project. The Met. Office, rightly or wrongly, has taken part in several COST projects over a very large number of years. What is the strength of COST? Well the informality and the fact that there is no money (laughter), some might say it is a talking shop, but in reality it is an enabling mechanism for getting like-minded scientists and engineers together with industry. This is what COST is about; encouraging European industry to transfer technology to commercial applications. Although the strength of COST is its informality, it does depend upon national programmes. Without the goodwill of the participants nothing would actually be done in COST.

Let us begin then by trying to put radar network developments within Europe into context. Roughly in 1970 Europe, USA, east and western Europe and Japan were more or less at the same position in terms of radar networking, not in terms of radar meteorological science, but certainly in terms of networking. Many countries had networks of analogue radars, but from that point on developments started to diversify. The Japanese started to digitize all their radars, and being Japanese they did this almost instantaneously, such that they now have the densest radar network in the world, and have actually gone further and Dopplerized some of the radars. I'll say a little more about Doppler radar later, but basically a Doppler radar, as well as measuring precipitation, measures wind speed and direction (direction with a little bit of ingenuity). Eastern Europe is more or less in the same position now as it was in 1970. The eastern European countries still have a very dense network of analogue radars, and many of these are actually dual frequency radars which is something we don't have many of in the west. These radars operate at two frequencies (usually X and S band), and that has provided some interesting science although most of the science has been carried out using analogue data. The situation may change very rapidly because of their

involvement in COST, certainly Hungary, Czechoslovakia and Poland, in particular, are actually seeking now to modernize their National Meteorological Services and, providing money can be found, action will be taken. The money will obviously limit what can actually be done.

In America things began to take off rather slowly from 1970. There was a project known as D-RADEX concerned with digitizing an analogue radar and trying to measure precipitation quantitatively. It actually paralleled fairly closely the work which some of you may have heard of, the Dee Weather Radar Project at the beginning of the 1970s which was carried out in North Wales, and in which the Met. Office played a leading role. A further project known as RADAP extended the digitization programme in the USA. These were really projects concerned with one or two radars, and looked at how to digitize them, and how to develop them for operational use. However, there was no very strong radar networking programme until work began on to the specification of the NEXRAD (NEXt generation RADar) system and its associated communications and display system AWIPS-90. This project aims to establish perhaps the most sophisticated radar that has yet been deployed, to be used by operational meteorologists. It is a Doppler radar, a high-powered system, and I will return to this subject later in my talk to give an indication, as to the type of performance these systems can have. However, what you should remember is that they are of an order 2 or 3 times as expensive as the kind of Doppler radars that we are familiar with in Europe.

Coming back to Europe, several European countries by 1970 had established radar programmes. I have already mentioned the Dee Weather Radar Project in the United Kingdom which was concerned with looking at whether you could measure precipitation with a digital radar. There was similar work going on in Switzerland and similar work starting in Sweden. In a sense, these projects were brought together by COST-72, which was the forerunner of the present project, concerned with investigating whether you could actually make quantitatively useful measurements with a digital radar. As we will see shortly, COST-72, certainly in the rest of Europe, although perhaps not in the United Kingdom, stimulated the rapid deployment of digital radars, and this trend has continued during COST-73. COST-73 has led to specifications for new technology projects, and proposals for operational implementation of international exchanges of radar data, so it could be argued that the COST programme has been the catalyst for rapid developments in operational radar networking in Europe. Just to follow that up, this is the actual deployment of radars that took place from 1970 to 1995 (Fig. 1). In 1970 there was a single digital weather radar in Europe, and that was actually located in northern Sweden. It was a military radar, and it can be seen from the figure that in the next 20 years there was an almost exponential increase in the deployment of digital radars

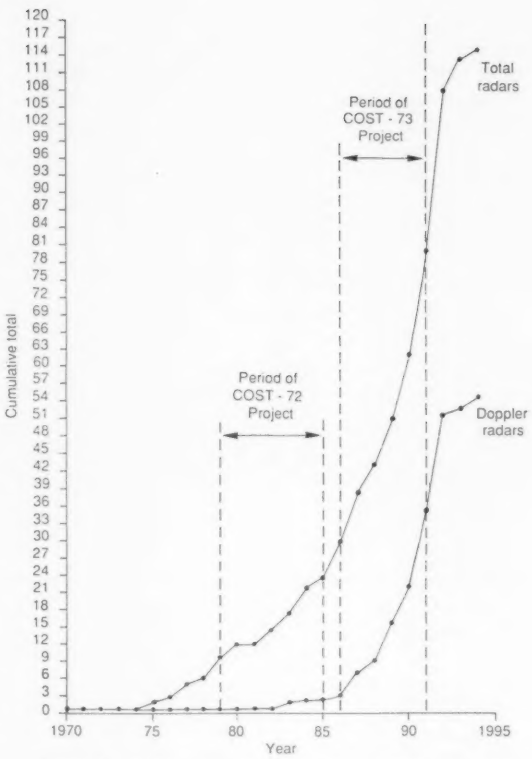


Figure 1. Radar deployment in European COST countries.

in Europe, spanned by the COST-72 and then COST-73 projects. In fact almost parallel to that deployment, starting in round about the early 1980s, a similar deployment of Doppler radars began, although that seems to have peaked for the time being. Doppler radars measure winds as well as precipitation. You can see that now there are approaching 100 digital radars in western Europe of which about a third are Doppler radars.

So what has COST-73, done and how was it structured? Well first of all COST-73 involves pretty well every country in western Europe and included as a full participant the European Commission itself. It involved all these countries and they pooled their expertise through the management committee of the project. The work, which I'll talk about in detail in a second, was tackled in two ways: offline studies involving asking all these countries how they were processing data and what were their plans, how we might use their data in radar networks, and real-time sub-projects. The aim was to demonstrate if data could be actually transferred between countries, and whether it was possible to use European-wide data in ways which were useful. The work was roughly partitioned in that way.

The work covered all aspects of radar networking, starting with the radar systems themselves, the characteristics of the radar hardware, what they could and

couldn't do, and, most importantly, what radar systems were just round the corner that might actually produce some new information. Various work was carried out trying to detail (really for those countries that were just starting off in networking) how to write a specification for radar network software. Clearly European industry was involved in this programme as members of the Management Committee; representatives from the Ericsson radar company in Sweden, Siemens Plessey in the United Kingdom, Gematronik in Germany, SMA in Italy and various software houses have been involved, and one had to write this type of specification to a rather high level. Also, specifications for display systems for radar network data were reviewed. Underpinning most of the work was analysis of data transmission methods and standardization of codes. Data transmission underpins so much of radar networking, so it is a very important topic that had to be addressed. We looked at bilateral data exchanges. These are already beginning to move ahead. The United Kingdom has exchanged data with the Republic of Ireland for some years now, between the Shannon radar and Bracknell. Likewise France exchanges data with Switzerland. During the project some (if you like) 'rules of play' for these exchanges were partially developed, but I will come back to this later. It is necessary to look at actually who wants all the data from other countries. COST-73 examined the requirements, data archiving, how to sensibly exchange data in real time, and how to operate Doppler radars within a conventional radar network because some countries have Doppler radar and some countries don't. Finally, and this caused untold problems, it was actually stated in our terms of reference that we must look at a *modus operandi* for a co-ordinated European Weather Radar Network. This led to some political difficulties.

What were the kinds of real-time project that we looked at? A composite image using data from several countries was produced in COST-72, and this work was carried on in COST-73 with some improvements and extensions to include other radar data. We looked at whether you could use radar data generally, and specifically COST data, for detecting severe weather and I'll touch on these severe weather algorithms a little later. An experiment was carried out both in the United Kingdom, at London Weather Centre later Aberdeen, and in the Netherlands to try to assess the utility of COST images to forecasters responsible for forecasting in maritime areas in the North Sea. I will touch on the results later. COST-73 began in the post-Chernobyl era, and of course here in the United Kingdom in particular we led the way in using wide area radar data to say something about where radioactivity was going to be deposited.

I have already shown the rapid growth in radars in Europe (Fig. 1) but how does this transfer into actual radar distributions in all countries. Have all countries got the same densities of radars? Well of course the answer is 'no'. Fig. 2 shows the present coverage from weather radars in Europe where the shading represents the lowest radar beam that is used, really the coverage where the radar beam is below 1½ kilometres above the surface. You can see that there is a very dense network of radars being installed now in Spain, for example, and really throughout the whole of northern Europe there is a very dense radar network. There were, before the current troubles in Yugoslavia, a lot of radars in Croatia and we think some of them have been destroyed. So this is a little bit out of date. The square frame here is the area over which the United Kingdom on behalf of COST produced European radar composites beginning with the COST-72 project and carrying on right through COST-73. These images were distributed to a number of countries including Finland. The open areas in Fig. 2 show radars which are planned, but not yet installed, although firm plans have been made with funds being committed. No radars are shown over Poland, Czechoslovakia, Romania and other Eastern European countries. In fact there are a lot of radars in these countries but they are analogue systems, as I have already mentioned. It is likely that radar coverage over the next few years will increase quite significantly. Fig. 3 shows the radar installation at Hohenpeissenberg in Bavaria, complete with Christmas tree, to prove that the United Kingdom doesn't have any prerogative on radar design.

Besides the conventional type of radar, Doppler radars can detect motion towards the radar and away from the radar within a range of plus and minus 48 metres per second. This information can be interpreted by making certain assumptions to give some information about the actual motion as opposed to the radial motion towards and away from the radar. Fig. 4 shows an example of the radial motion display. This is the actual type of data that one gets out of these radars. The colours represent the motion towards the radar and away from the radar so the blue colours are, I think, towards the radar and the red ones are away from it, a convention which they happen to use in Sweden as this is a Swedish radar. We in the United Kingdom are getting such a radar. It'll probably be installed in south-west England at Cobbacombe. Fig. 5 shows the kind of information that we can derive from the types of image shown in Fig. 4. Height against time is plotted, and the contours are actual wind speed. In a single Doppler radar you really don't get the three-dimensional motion vector, so it may be appropriate to interpret these data in the context of a numerical model. In Sweden they have actually started to do this, and they can produce measurements of wind velocity, but only where there is precipitation, because these radars in Europe are of low power and in general do not make measurements in the clear air. In the USA with their NEXRAD systems, which are very high powered systems, and they can actually make measurements in the clear air. So NEXRAD will be able to observe clear air turbulence for example, and a whole variety of phenomena which

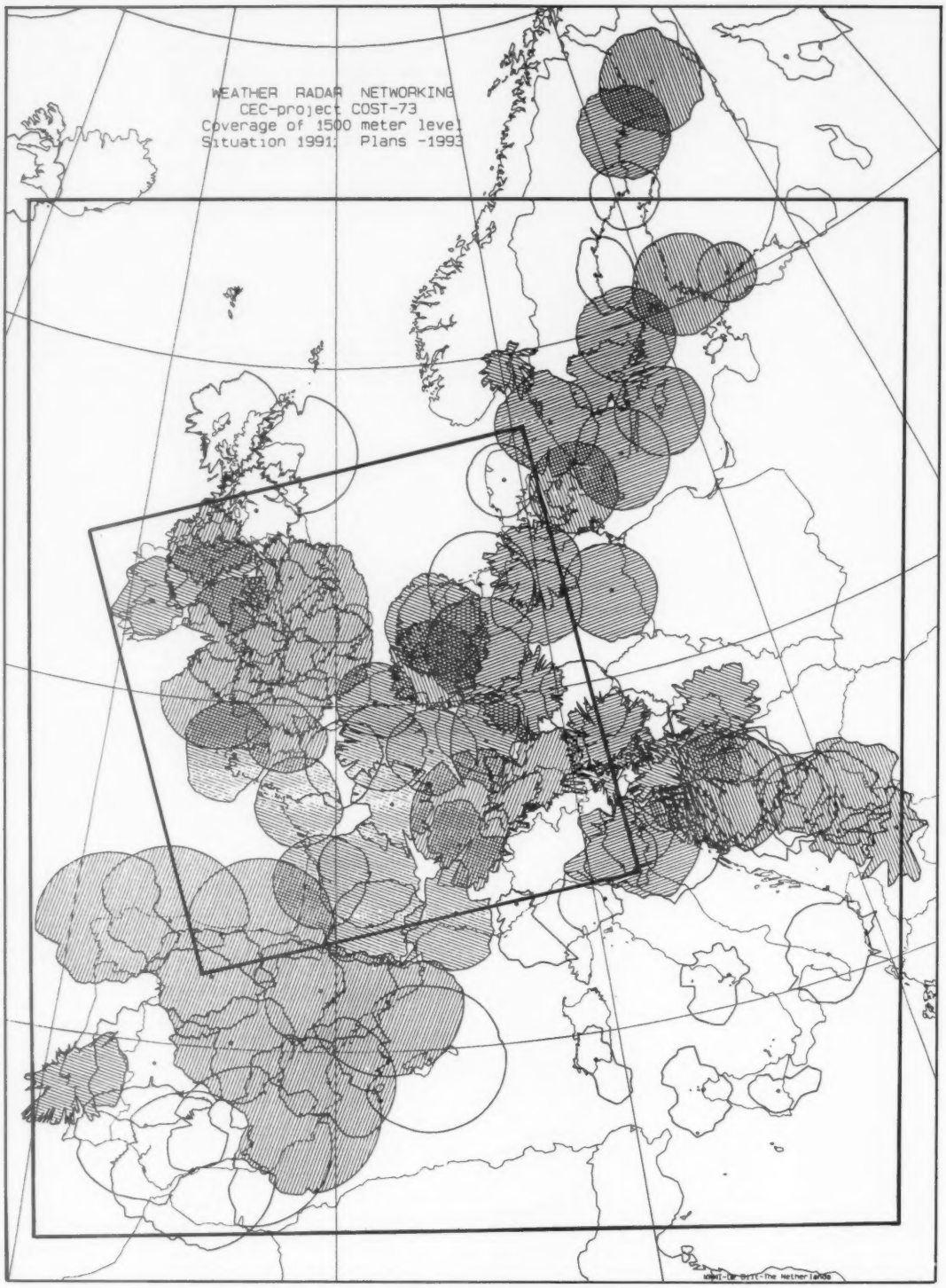


Figure 2. Radar coverage in 1991, with plans to 1993 unshaded.

Figure 3. Radar installation at Hohenpeissenberg, Germany.

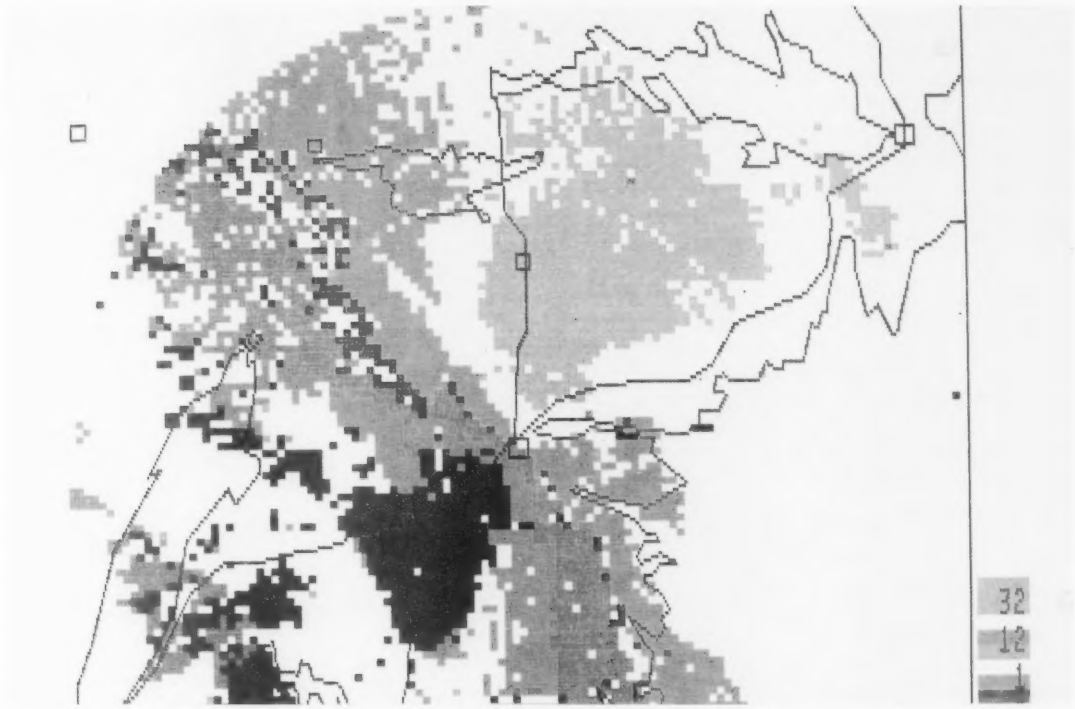


Figure 4. Example of radial motion displayed from a Doppler radar located at Norrköping, Sweden. (Courtesy of Ericsson Radio Ltd.)

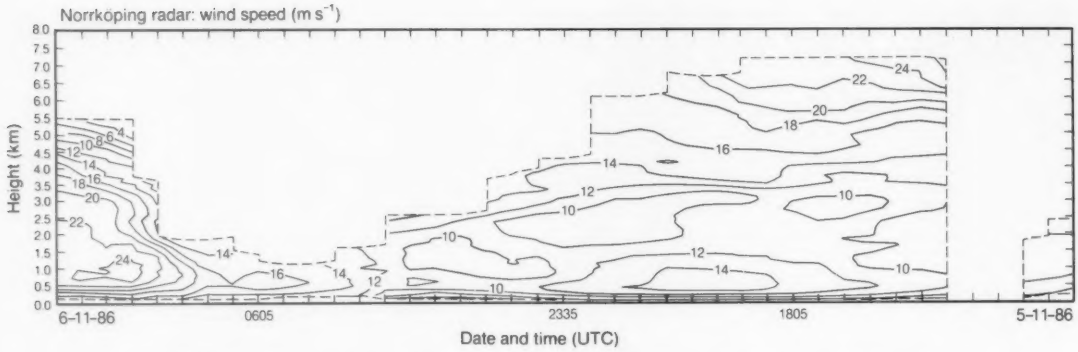


Figure 5. Example of wind data (m s^{-1}) derived from displays such as Fig. 4. (Courtesy of SMHI.)

perhaps we won't be able to detect except at very close range. In the United Kingdom we really need to investigate what we can and can't see with low-power Doppler radars. So what is the benefit of having Doppler radar if you cannot make measurements in clear air? Well I have mentioned the wind measurements where there is precipitation, and you could also use these systems to partially suppress ground clutter. Ground clutter, echoes produced where the radar beam hits the ground, varies only slowly in time, so if you can measure the motion of the echo fields then you can discriminate between moving rain and the not-moving ground echoes. However, it is not quite as easy as I have implied. In addition, Doppler radars also make measurements of the turbulent structure of the atmosphere by measuring the velocity spectrum of the turbulent motion. Fig. 6 shows the frequency of echoes in 2 dbz intervals so what we are looking at here is the frequency of occurrence of echoes in the area of a ground echo shown by the dashed line, and the solid line is the frequency of echoes where there is rain. With a Doppler radar you can actually remove most of this ground echo. I mentioned that Doppler radar can only partially cancel ground clutter and, for example, if you have orographic rainfall that is stationary, then obviously a Doppler radar can have trouble discriminating that from other ground echoes. We need to employ a whole range of techniques to remove ground clutter, and all these have been reviewed in the COST-73 project. One of the things that will come out of this project, in the final report, is some critical assessment of the way in which we should go about improving cancellation of ground clutter. This is quite important because when we look at the radar images on TV, we don't want to be confused by looking at ground echoes, we want to look at rain. If we can improve the procedures currently employed, perhaps in an automated fashion, then so much the better — it takes a load off the forecaster, and hopefully provides corrections in a more reliable fashion. Consequently there is a large degree of interest in these kinds of technique.

Still on the radar systems, there are also newer advanced radar systems. Dual frequency radars exist in eastern Europe, but there are all sorts of other radars,

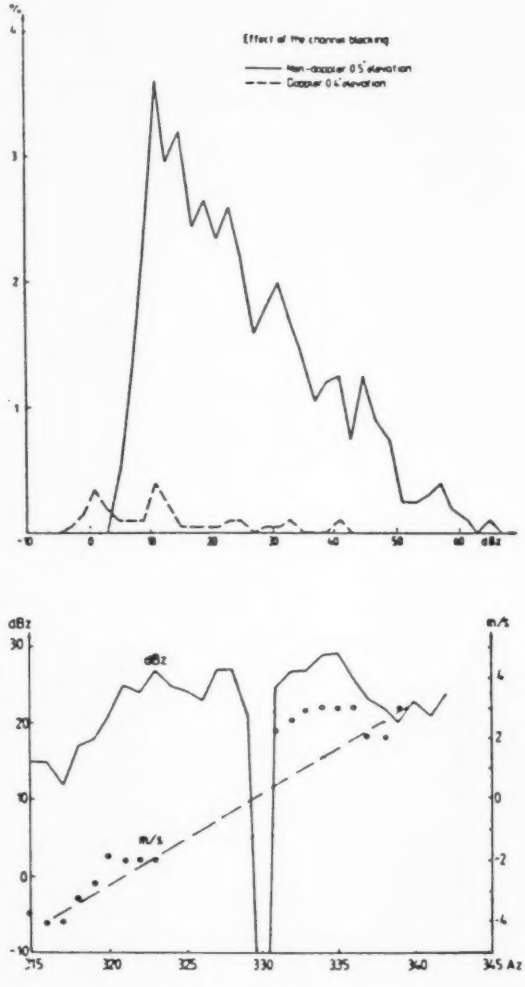


Figure 6. Frequencies of echoes per 2 dBz interval in the vicinity of a ground echo. The area of investigation was azimuth 220–230° with range 30–55 km. The antenna elevation is 0.5°.

including dual polarization radar. You may have heard of the Chilbolton radar which allows measurements to be made of the actual characteristics of the hydrometeors we are looking at, using parameters based upon polarization and phase differences in the radar beam generated by rapid electronic switching between circuitry. Electronic scanning radar is also a possibility where instead of having the conventional metal dish, you actually have a phased electronic array to produce the beam. COST-73 has looked at the range of radar types.

The electronic scanning radar is not brand new technology. Most defence radars are actually electronic scanning radars. Fig. 7 is one such device which detects little metal objects flying at high speeds and low elevation. It is the MESAR radar produced by Siemens Plessey Radar Ltd, and the figure shows the phased array that is normally behind a cover. The whole assembly rotates mechanically around a vertical axis, but scanning in the vertical using phased array technology. This could be adapted for meteorological use, and provide three-dimensional measurements of the atmosphere instantaneously. This is attractive, but the problem is, of course, the development cost. Investigations are beginning with several companies to look in detail as to whether this technology can be transferred to the civil sector at a reasonable cost. Why are we interested in all these fancy radars? Well I mentioned earlier that the technology that we are presently using is 25 years or so old. In another 5 years the United Kingdom and other countries will have to start replacing their older digital radars, and if this is going to happen what kind of technology should be considered? This is why there is quite a lot of interest at the moment.

Moving from the radar sensor itself, COST-73 has been responsible for intercomparing the characteristics of all the radar networks from all western European countries. Table I is an example of the comparisons which have been produced. This example shows the average radar area and the beam size which are used in the radar network for particular countries. In the United Kingdom the area per radar in thousands of square kilometres is the lowest of all the radar networks in western Europe so we have the most dense network. However, you can see that Spain in 1989 has a coverage of 500 000 square kilometres per radar which drops rapidly to 33 000 in the next year or so. There are a whole range of items including comparisons of the measurements of precipitation, who does what and how they do it. All this information is contained in the COST-73 Final Report.

Turning to severe-weather definitions, it is actually amazing how different the definitions of severe weather are in the different countries around Europe. Table II gives a few: Austria, Norway, Spain, and you can see that the one common thread that goes through them all is thunderstorms which perhaps cause the most serious problems: heavy rainfall, hail and so on. Nevertheless there is a whole range of definitions which are used in different countries. In addition, severe weather algorithms for radar have been reviewed. Just to illustrate some of these algorithms, Fig. 8 shows Russian work giving height as a function of the reflectivity measured by the radar. These reflectivity profiles in the vertical may be interpreted in terms of the different types of weather including thunderstorms, very deep precipitation, and small cumulus clouds giving low precipitation rates. Scientists such as Albert Waldvogel in Switzerland have

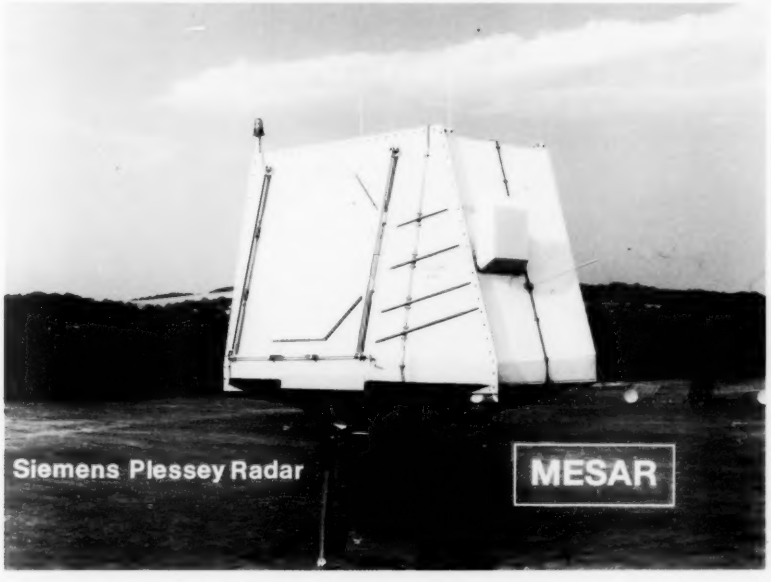


Figure 7. An electronic scanning radar without its cover. (Courtesy of Siemens Plessey Radar Ltd.)

Table I. Answers and calculated results from the questionnaire of COST-73 existing and planned radars

Average Area and Beam Size

Country	No. of radars		Area per radar 1 000 km^2		Average range km		Average beam dia. [3dB] km	
	1989	1993	1989	1993	1989	1993	1989	1993
Austria	3	4	28	22	92	80	1.8	1.5
Belgium	1		50		121		2.1	
Denmark	1		43		113		1.8	
Finland	3		112		83		1.6	
France	11		50		121		3.0	
Germany	3	10	183	25	157	86	3.0	1.7
Ireland	1		70		145		2.5	
Italy	2	15	162	22	217	79	3.2	1.2
Netherlands	2		20		77		1.5	
Norway	1		386		340		5.0	
Portugal	1		93		166		3.2	
Spain	1	15	500	33	387	100	6.1	1.6
Sweden	3		133		200		3.0	
Switzerland	2	3	20	13	77	63	1.5	1.2
United Kingdom	8	13	13	8	61	48	1.1	0.8
Yugoslavia	4	13	64	10	138	100	2.4	1.8*

* 3.5 km for XS band radars

Note:

The table gives the number, area per radar and average distance and horizontal extension of the radar beam for existing and planned radars as reported in COST 73. The average distance from the radar is defined as the true average distance to the closest radar (all radars equally spaced) multiplied by 1.5 because of non-regular spacing of radars (= 0.54 SQRT (Area)). The average horizontal extension of the radar beam is the extension of the beam at this distance, considering the actual 3 dB width of the beam as indicated by each country.

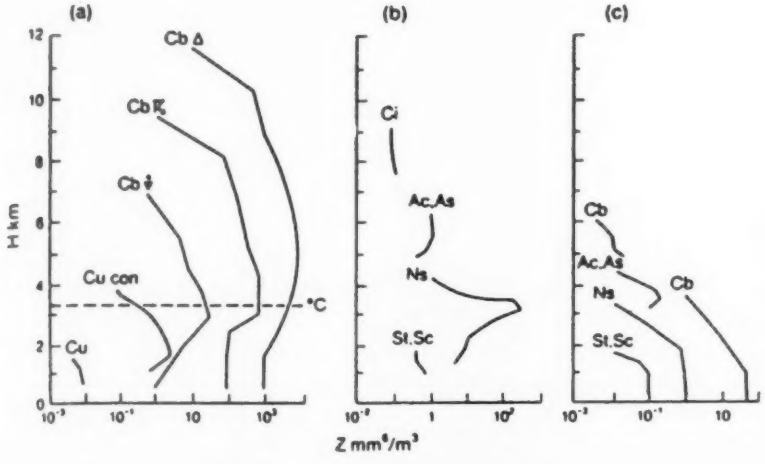


Figure 8. Vertical reflectivity profiles related to severe weather occurrence and cloud type.

Table I. (continued)

Receiver and Range Correction

Country	Receiver						Range correction	
	lin		log		from	to	log	lin
	range dB	toler. dB	range dB	toler. dB	km	km	dB/dek	dB/km
Austria			80	+2/-0	5 (s)	230	20	0.017
Belgium	35	0.5	75	0.5	5 (s)	240	20	
Denmark	92	?	?	?	2	240		
Finland			70	?	1	300	20	0.015
France			70	+/-1	5 (hs)	100		
Germany			95	+/-0.5	1 (f)	230	20	0.016
Ireland			64	+/-0.5	4 (s)	200	20	
Italy	45	+/-1	>80	+/-1	1 (s)	400	20	0.015
Netherlands			80	1.5	2 (s)	128	20	0.005
Norway	87	0.4	85	0.4	1 (s)	240	20	0.015
Portugal			80	0.5	4 (s)	200	20	0.015
Spain	86	0.4	86	0.4	1 (s)	240	20	0.016
Sweden	85		85		1 (h)	480		0.016
Switzerland			90	+/-0.5	5 (s)	230	28	0.017
United Kingdom			70	1.0	5 (hs)	210	20	0.017
Yugoslavia	90	1	85	+/-0.5	5 (s)	200	20	0

Note:

Range correction made in software (s), hardware (h) and/or in the firmware (f) (read-only memory).

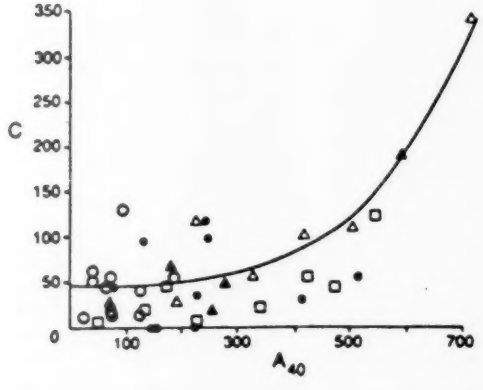


Figure 9. The peak radiated field for five storms as a function of the 40 dbz contour.

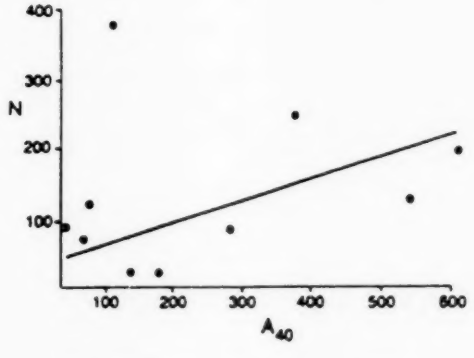


Figure 10. As Fig.9 but for flash frequency.

Table II. Examples of some severe weather definitions

AUSTRIA

- Thundersorms
- Thunderstorms with hail
- Intense snowfall (6–12 hours)

NORWAY

- Precipitation 3–4 mm/10 minutes in north
  7–8 mm/10 minutes in south
  6–11 mm/30 minutes
  Freezing > 0.5 mm h^{-1}
- Heavy snowfall 2 cm h^{-1} (4–5 mm h^{-1})
  First snowfall in autumn — 0.5 cm
- Wind gusts > 25 m s^{-1} inland
  > 28–39 m s^{-1} coastal areas

SPAIN

- Heavy rain $\geqslant 50$ mm in 12 hours or $\geqslant 15$ mm h^{-1}
- Strong winds > 25 kn
- Visibility < 100 m
- Snow
- Mountain waves
- Strong wind shear
- Hail

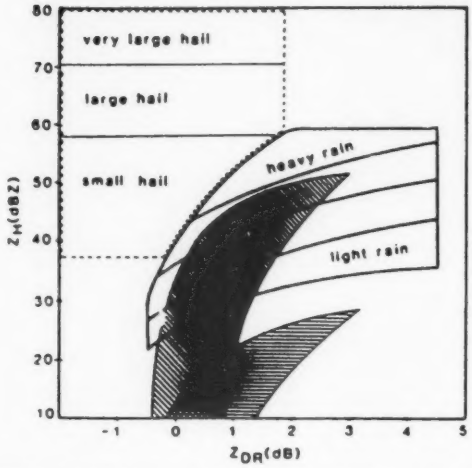


Figure 11. Reflectivity and differential reflectivity fields as measured by the Chilbolton radar.

actually come up with little algorithms relating radar reflectivity to the occurrence of hail. If the 45 dbz contour exceeds the height of 0 °C isotherm by more than 1½ kilometres then there is a high probability that hail occurs. In Figs 9 and 10 is shown another type of algorithm which is beginning to be used to detect lightning from radar information. The peak radiative field of lightning is shown as a function of the area of the 40 db contour. It is evident from the scatter that this relationship is not very reliable, but nevertheless just by looking at the radar image you can get a probability that the particular storm you are looking at is actually producing lightning. We don't use any of these in the Met. Office at the present time, and this is rather a pity considering the quality of the radar pictures we have.

If we move on to Doppler radar, then there are a whole range of new algorithms to look at. A relationship exists between maximum hail size and the divergent flow which you can measure from Doppler radar, and there appears to be a pretty good relationship between these two quantities so that one can say something about hail size. Hail detection is perhaps not a major problem in the United Kingdom, but elsewhere in southern Europe it is. Also, by measuring the low-level flow you can make some statement about whether you are likely to get a tornado or not. A debate at the moment in Europe, particularly in Spain, is whether you can actually make the necessary measurements with these low-power radars that we have in Europe, because much of the published research work has been carried out in the USA with radars which are very powerful. Those in southern Europe in particular, believe they have a serious problem with downbursts, tornadoes and things like that, and they are particularly concerned with these types of system.

Finally, if there is access to a dual polarization radar, it may be possible to say something about the differences in the radar echoes when heavy rain, hail or other severe weather types are present. Fig. 11 shows reflectivity as a function of differential reflectivity, ZDR. We haven't time to go into the definition of ZDR, but with this kind of radar you can say something about precipitation type.

So that is the radar sensor; turning now to the radar network itself. Fig. 12 is an example of a fully configured data network, and I think if you look at the figure you will see that system elements are pretty well backed up. Imagine a radar being located at each of the nodes, then there is dual communication between each site. You can establish a particular network architecture based around a computing system where the network centre is going to be. This is similar to what we have in the Met. Office. We have a local area network, we have various computers hanging off it. In the COST-73 project we have looked at these general architectures for radar networks, and then compared them against the architecture used in practice. Fig. 13 shows an architecture which is increasingly being used by quite a number of countries. You can see that it is somewhat different from the ideal structure shown in Fig. 12. Mostly the telecommunications of the sites are not backed up, cost dictating that there is a single communication link between the radar and the central compositing centre. If for comparison we just look at our own network in the United Kingdom the telecommunications configuration is a star arrangement, very similar to that shown in

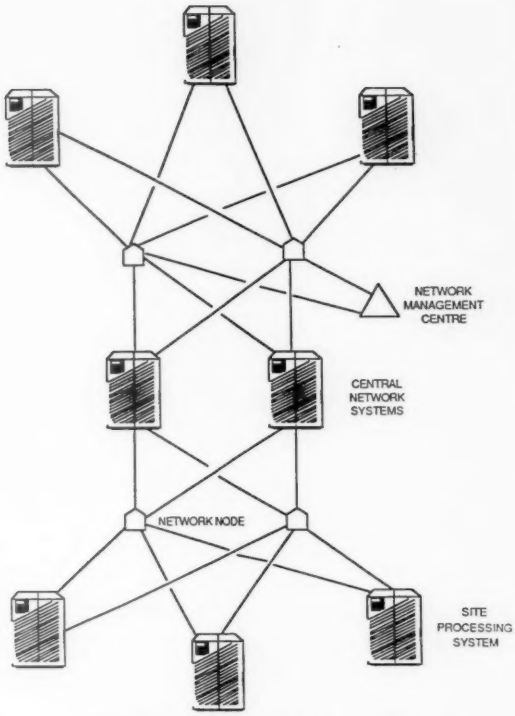


Figure 12. A fully configured data network.

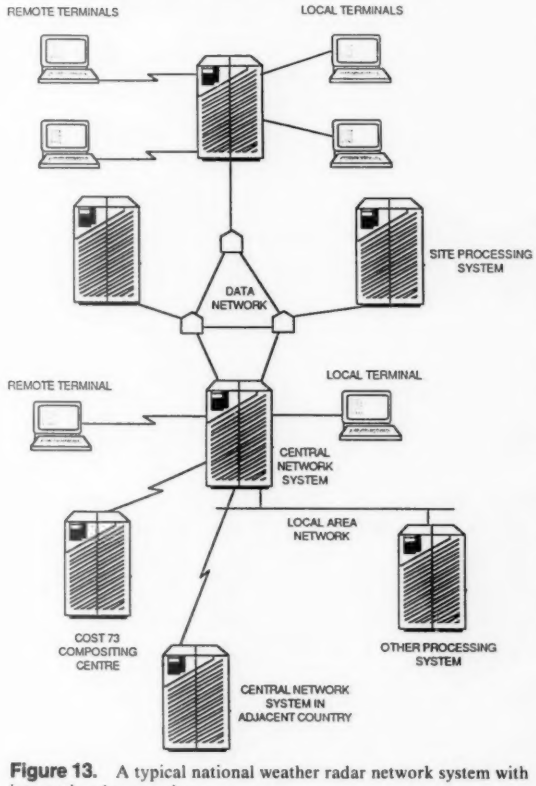


Figure 13. A typical national weather radar network system with international connections.

Fig. 13, with all the radars sending their data to Bracknell. This kind of structure is being reproduced throughout Europe. Germany, for example, has established a network very similar to this. Most countries cannot afford to have duplicate communication links.

So what has COST-73 done for communications in radar networks? A considerable amount of effort, led by a working group chaired by France, has modified WMO FM 94 BUFR code to cope with radar data, and the modifications have been accepted by WMO. We are in a position now to use this standard WMO code to exchange radar data between countries. Although I have mentioned this quickly, this work represents an enormous amount of effort lasting just about most of the 5 years of the COST-73 project.

In order to try to investigate some of the communication problems likely to be encountered in radar networks, the Project utilized the WMO GTS. Experiments were carried out to exchange some data between centres on an experimental basis. Largely through the good offices of the Met. Office Telecommunication Department we were able to use the GTS on an experimental basis using existing codes (ITA5 not BUFR) to transfer data between Bracknell and Finland, Bracknell and Paris, Bracknell and the Netherlands, and Bracknell and Ireland. This led to investigations of data compression techniques. A comparison of various compression algorithms including BUFR, because BUFR code itself produces a degree of compression of the data, has been looked at within the Project. I am bound to tell you that no definite conclusion has been arrived at about which compression algorithm is best, but we do at least have some objective information on performance.

Finally on communications some of you may have noticed that we did all of a sudden have a satellite dish appear on the roof of the Richardson Wing. This is a terminal which in theory would have allowed the transfer of radar data via the Olympus satellite, and between Austria (Graz) and Bracknell on an experimental basis. The equipment was borrowed from RSRE Defford with the help of ESA Estec. Everything was set up all ready to go, but the satellite developed problems on the day of the first full test. Recently (March 1992) the satellite has come back, and tests have resumed.

If we move from the communications to the central compositing. What do meteorologists do when they have data from a number radars? Table III shows an example of the range of central processing carried out at network centres in western Europe. You can see that, for example, 19% of countries send the raw data to the compositing centre then remap them to produce a composite image. Here, remapping is a transformation from polar to Cartesian coordinates, while 81% of the radar installations in Europe carry out remapping at the radar site, 57% of these networks use fixed boundaries like we do in the Met. Office. Use of fixed boundaries means that if a radar is lost, then the boundaries change.

Table III. Combination of data from different radars

(a) Change of grid and projection compared with a single radar

Country	new grid size km	method comb.	project type	method reproj.	before merging?	changed where?	merged where?
Austria	2	=	rectang.	=	=	=	display
Belgium							
Denmark							
Finland	7.1	max: 9	psp	table	during	centre	centre
France	3	=	psp	=	=	=	centre
Germany	4	max: 4	psp 10E	=	after	centre	centre
Ireland							
Italy							
Netherl.	2.4	=	psp	=	=	=	centre
Norway							
Portugal							
Spain	4	av. rain	lambert	=	before	radar	centre
Sweden	4	max: 4	psp 14E	=	during	centre	centre
Switzerl.	2	=	rectang.	=	=	=	centre
U.K.	5	av. rain	trv.merc.	=	before	radar	centre
Yugoslavia	2	=	rectang.	=	=	=	centre

(b) Combination of data from different radars

Country	input data	overlap data choice	boundary choice	other composite products (planned)
Austria	max. vert. col.	max	-	(1)
Belgium				
Denmark				
Finland	max. vert. col.	max	-	high resolution composite
France	low elevation	no	nearest avail.	
Germany	low no clutt.	max	-	
Ireland				
Italy				
Netherl.	low no clutt.	max/swap	avoid clutt.	
Norway				
Portugal				
Spain	3 km CAPPI	max of 4	nearest 4	echotop; hourly rainfall
Sweden	low CAPPI	no	optimum	echotop;max.vert. column
Switzerl.	max.vert.col.	max	-	(1, 2)
U.K.	low no clutt.	no	nearest avail.	
Yugoslavia	low no clutt.	lowest	to be defined	max. vert. column

(= no change; psp = polar stereographic projection, trv. merc. = transverse mercator projection)

(1) The composite includes side and front views.
(2) A full volume (12 layers of 1 km) product with linearly averaged rain-rate data is planned.

43% of countries use the maximum value in the overlap area.

So what do these COST images actually look like? Fig. 14 is one example at 2000 UTC on 7 March 1991, including data from the United Kingdom, France, Ireland, Switzerland and the Netherlands. The blue area is infrared data from the European satellite Meteosat, lighter blue being medium-level cloud and dark blue is high-level cloud, the other colours are radar data. Also shown are the coast of France, the coast of Spain, the Bay of Biscay, the United Kingdom and Ireland, and political boundaries. The limit of the radar coverage is shown as a full or broken line. This kind of image is currently produced every hour. Most of the data are archived.

Work has been done in the project on uses of multi-national composites. I am going to look at these uses very quickly, starting with forecasting of rain. So far very little work has been done on how to use these kinds of wide-area radar data as a contribution to data assimilation within numerical forecast models. It is important that this work is done.

First of all the contribution of wide-area radar composites to general forecasting. Fig. 15 is an example showing a thunderstorm moving from off the Cornish coast at 1100 UTC right through France into Germany. The solid shading is the radar data, the lighter shading is the satellite infrared data. It is interesting to note that if you look at the time 1700 UTC in a region where I know there is good radar coverage, you can see the overhanging cirrus from the thunderstorm which certainly does not correspond to the rain area. Clearly, if you have international radar data then you can track systems for a very long way on many occasions. Of course we in the United Kingdom tend to be on the windward side of Europe, but those countries further into Europe have a real need for the data from the United Kingdom.

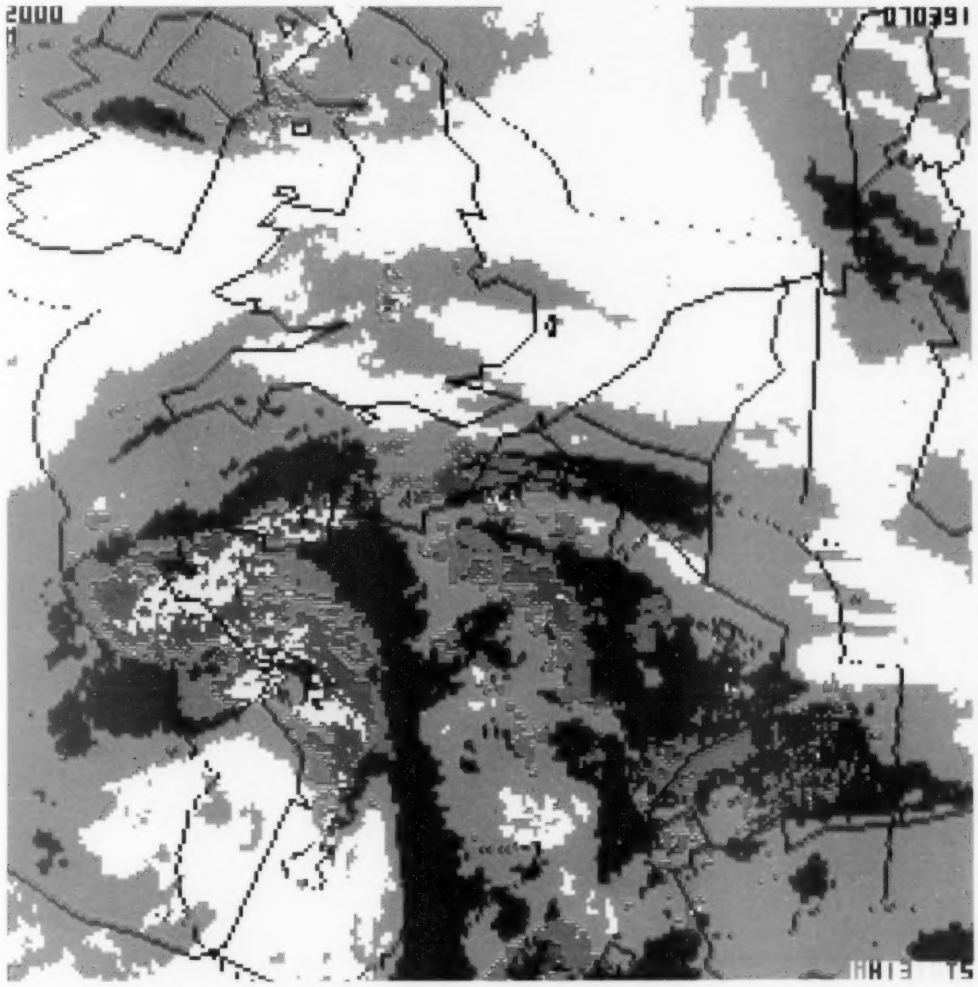


Figure 14. An example of a COST image. See text for full explanation.

Table IV shows the results of the assessment carried out at London Weather Centre, then at Aberdeen when the offshore bench was transferred there, and also in the Netherlands. To assess the utility of COST data for forecasting offshore, we distributed a questionnaire to the forecasters. If you look at the figures in Table IV, code numbers represent the precipitation types, and A, B, and C represent the quality of the guidance. A is good additional guidance, that is additional to the database that already existed, B agrees with other data and C is misleading advice from the COST data. The first thing to notice is that both in the Netherlands and the United Kingdom the results are more or less consistent. In addition, for roughly 36% of occasions the COST image provided good guidance for the forecaster. It is clear that this kind of data has a positive impact for this forecasting application.

Another application is the use of COST data for pollution monitoring. A numerical model developed at Imperial College by Helen ApSimon has been used to simulate the deposition of caesium from Chernobyl when the radioactive cloud passed over the United Kingdom, and she used as input to that model the radar data from the UK weather radar network to provide a measure of the precipitation that washed out caesium from the radioactive cloud. If you compare that model prediction and the actual distribution of caesium, there is good correspondence. From that start David Goddard and Brian Conway have developed a procedure for estimating the best precipitation field using radar, satellite and numerical model data. Fig. 16 is an example of the resultant field, where the different colours on this particular display represent the different types of data. These data are used as one input to the NAME deposition model, developed by a team led by Barry Smith and Roy Maryon. Many countries are now very interested in using radar data in this way because there are rather a lot of nuclear power stations, quite a lot of them very similar to Chernobyl, and it is important to be prepared.

Scientific understanding could be advanced by the COST data set which is just waiting to be used. To try and illustrate what we might attempt to do, Fig. 17 shows a COST image (again, the blue is the satellite data) in which the infrared is not making any sensible measure of the surface precipitation at all. It is a complete mismatch over most of France and the Low Countries. Over south-west England and Ireland the satellite and radar data are much better matched. The Met. Office hosted a multi-national experiment in February and March 1991 aimed at collecting as much satellite data as possible over north-west Europe with as much rain-gauge and radar data as possible, to allow scientists to test their satellite algorithms for estimating precipitation. The European radar data are proving to be a very useful source of data for these kinds of assessment. An example of the use of this imagery in research into the development of mesoscale conceptual models is shown in Fig. 18, an example of a split front; there is clearly a lot of information in these images.

Table IV. Assessments of COST-73 for maritime forecasting — from various users

London Weather Centre;
138 observations November 23 - December 21, 1989

Situation:	0	1	2	3	Total	% 1-3 only
%A	0	3	0	2	5	10
%B	35	38	0	9	81	86
%C	12	2	0	0	14	4
	46	43	0	11	100	100

Aberdeen Weather Centre; 631 observations January 19 - May 6, 1991

Situation:	0	1	2	3	Total	% 1-3 only
%A	7	0.6	6	1	15	31
%B	45	5	8	2	60	62
%C	24	0	1	0.3	25	7
	76	5	15	4	100	100

Schiphol Airport; 1458 observations July 10 1990 - March 9, 1991

Situation:	0	1	2	3	Total	% 1-3 only
%A	4	8	2	4	18	36
%B	55	14	1	9	79	62
%C	2	0.1	0	0.6	3	2
	61	23	3	14	100	100

Hoek van Holland; 1458 observations July 10, 1990 - March 9, 1991

Situation:	0	1	2	3	Total	% 1-3 only
%A	3	7	2	4	16	27
%B	49	17	6	12	83	72
%C	0.1	0.3	0.3	0	1	1
	52	24	8	16	100	100

A = good additional guidance
B = agrees with other data
C = misleading

0 = no precipitation, 1 = front(s), 2 = active front(s), 3 = unstable air mass.

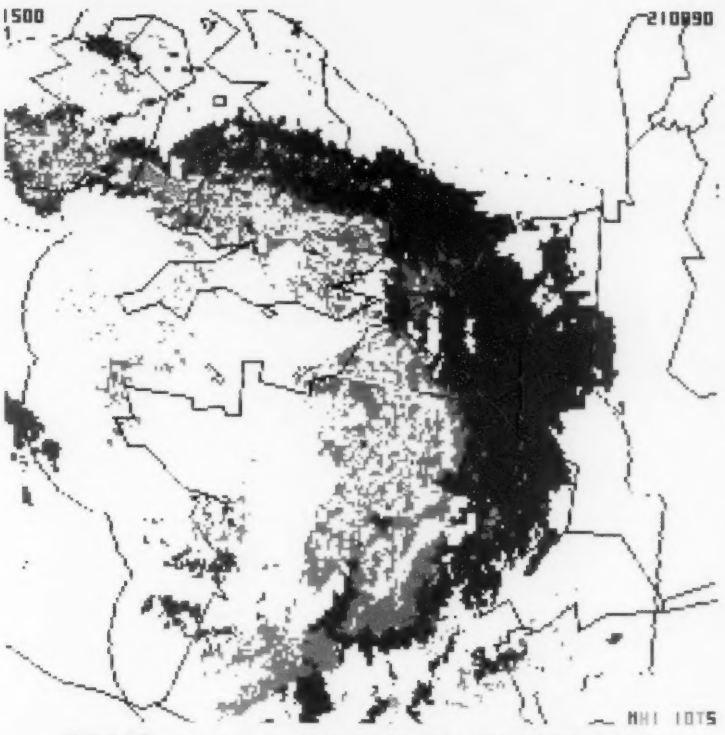


Figure 17. As Fig. 14, but showing a mis-match of radar and satellite data.

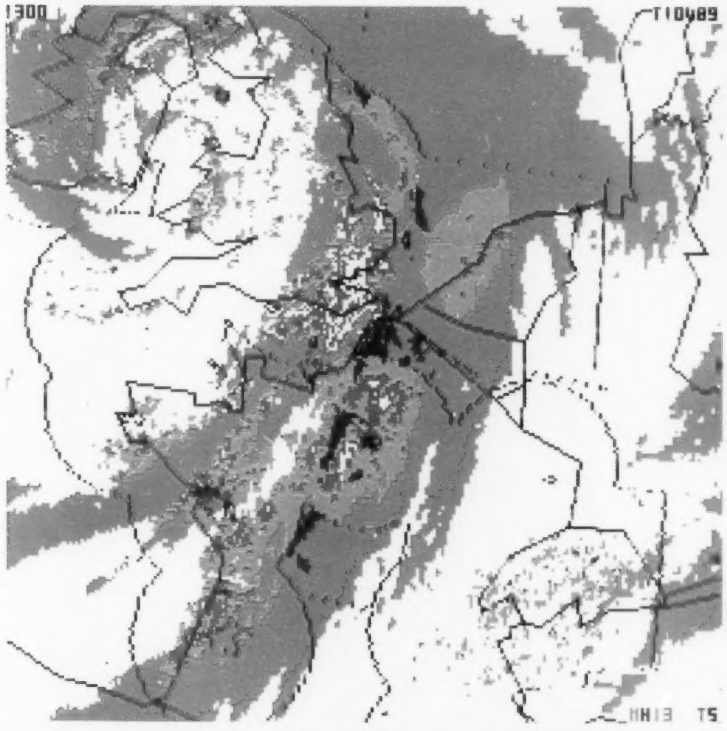


Figure 18. Example of a split front observed using COST data.

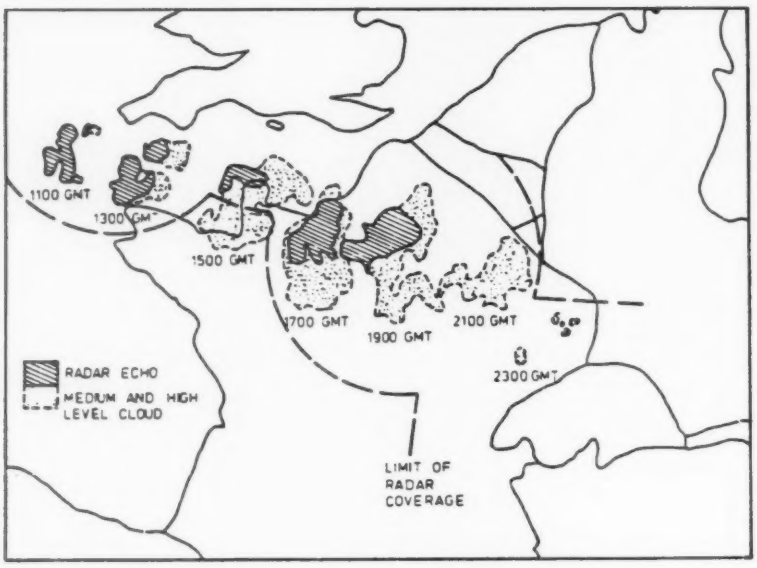


Figure 15. An example of a composite showing the progress of thundery activity across western Europe.

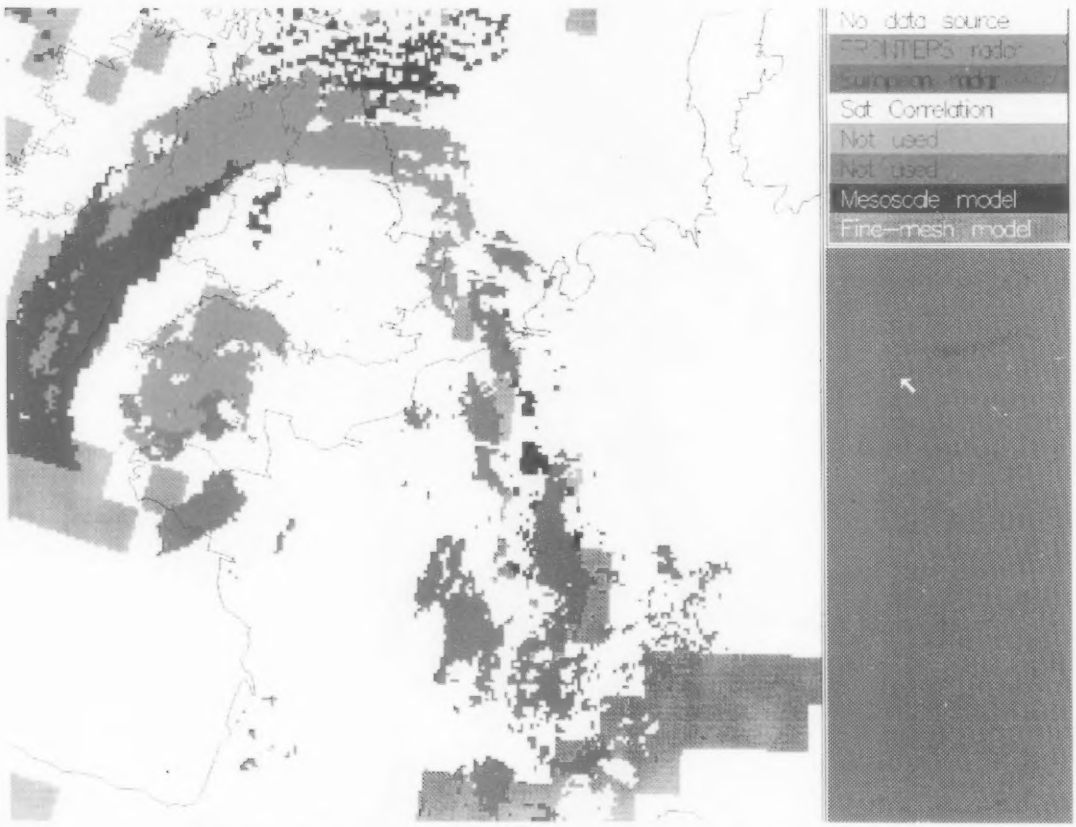


Figure 16. Estimated best-precipitation field from radar, satellite and numerical model data.

A further application of international radar data is as a contribution to continental-scale hydrology — looking at hydrological processes on a continental scale. Fig. 19 shows the international river basins over Europe. The Danube is the most international river in the world. It is bordered by the most countries, and the only way in which one can understand hydrological processes on the scale of the Danube is to use precipitation information on the scale of the entire river basin. That in Europe could mean radar data you can integrate.

Another application of these radar data would be as part of an international river watch. Some of you may recall in the papers some years ago when a company tipped a whole bag of chemicals into the river Rhine in Switzerland, and the pollution travelled all the way down the Rhine killing many fish. Hydrological models of water quality exist and are being developed on the basin scale. They need real-time precipitation input to make them fully operational.

The Met. Office have employed a company to look at possible commercial benefits from the use of COST images. They identified two areas in particular. Fresh food importers, who would like to go to individual farms in Southern Europe to select produce on the basis of whether it rained at a particular farm or not as it makes a difference to the quality of the produce they are going to buy. In addition, European TV Channels expressed particular interest. New types of user will necessitate the development of new products, and some examples have been proposed in the COST-73 project.

So what are the recommendations of COST-73? Table V lists the main recommendations. Of particular importance is operational network continuity. There have been some proposals that work started in COST-73should be continued, and that FM 94 BUFR should be used for international radar transmissions. There is a gap in the radar network coverage over the North Sea. Perhaps one or two Doppler radars could be established on platforms in the North Sea as shown in Fig. 20. Likely costs have been investigated and are not prohibitive, particularly if one recalls that Doppler radar will measure wind speed as well as reflectivity.

The technology of current radars is rather old, and a new COST action has been proposed (now designated COST-75) to look at new forms of radar technology, including electronic scanning and multi-parameter radars, and the algorithms and software needed to process the data from the radars in real time. This could lead to specifications for the next generation of radar in Europe. I am bound to say that there was some interest from scientists at the weather radar conference held in June 1991 in Paris. Scientists from NCAR looked at electronic scanning technology and decided that it was feasible some 5 or 6 years ago. However, they did not

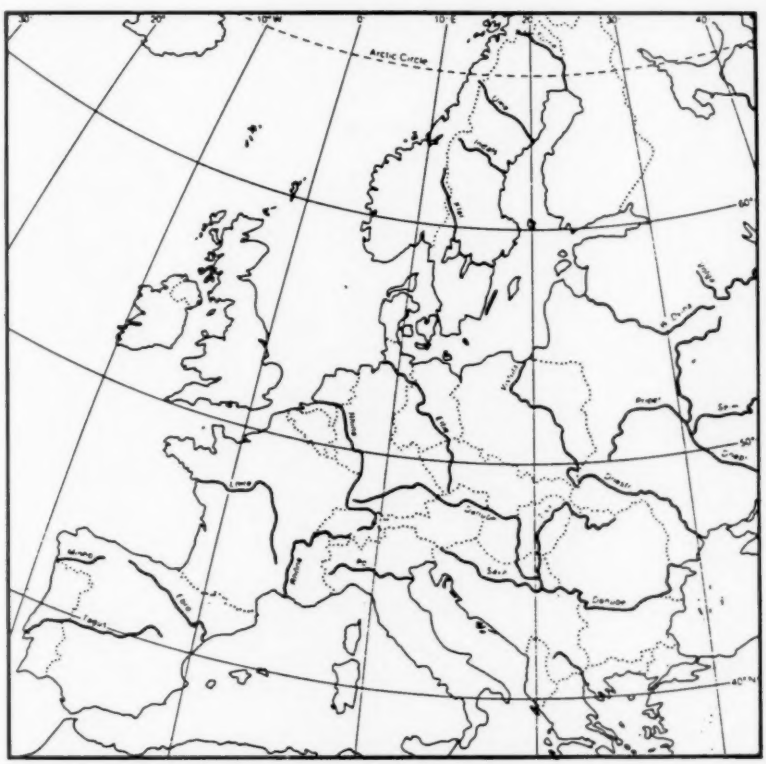
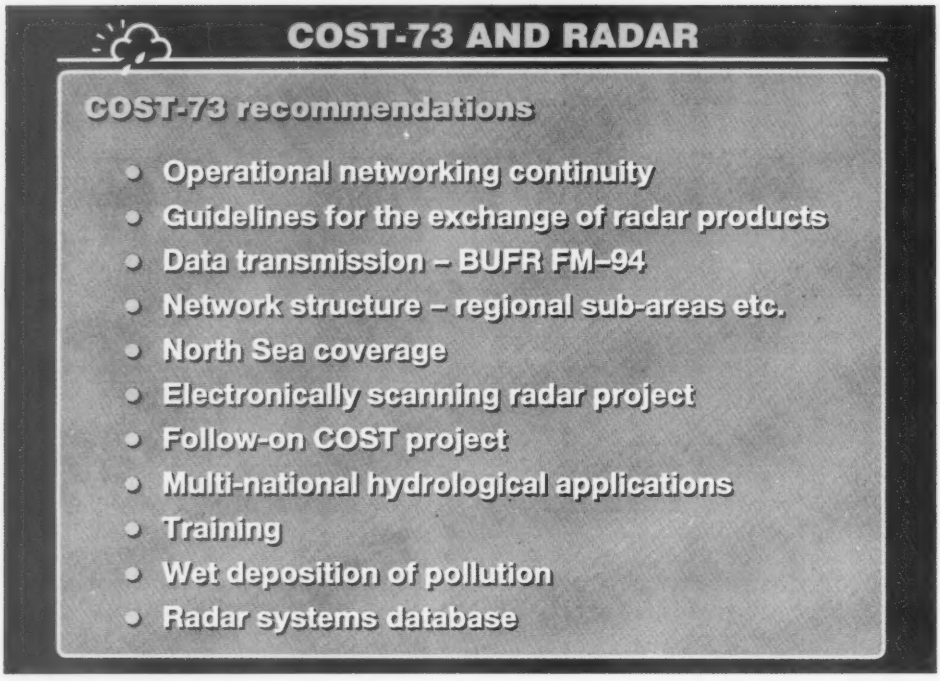


Figure 19. Map of the major river systems of Europe.

Table V. COST-73 recommendations



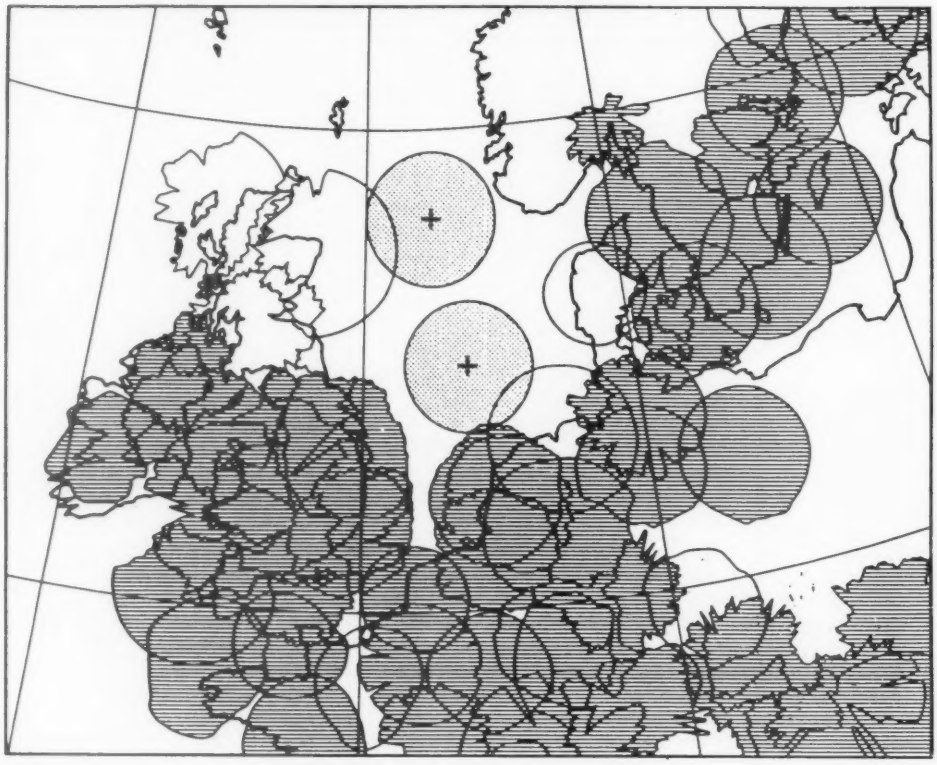


Figure 20. Possible location of North Sea radars.

take this further for surface radars, but instead transferred that technology to an airborne radar. However, when we showed them pictures of this type of radar being used for defence purposes there was some renewed interest from North America, and hopefully this will be pursued through the new project.

The COST-73 Management Committee felt that training in radar meteorology was totally inadequate, and the Committee specified, in some detail, a training curriculum that could be used as a basis for the training of technicians, meteorologists and users.

As the Project finished the Directors of West European Met. Services established a working group to look, in detail, at how work in COST-73 might be taken and transferred into an operational environment. The working group met in Florence in the summer of 1991, the Met. Office being represented by Kirby James and Francis Hayes. A report is due to be presented to the Directors of European Met. Services, and I hope they conclude that there should be a permanent group established to manage the international exchange of radar data around Europe. (Since delivering the lecture this has been agreed.)

I believe that COST-73 was a very successful example of international cooperation. A detailed Final Report has been completed and will be published by the European Commission (DGXII) soon. Without the efforts of many people this achievement would not have been possible. For me as Chairman of the Management Committee it has been marvellous project, and one which I feel very fortunate to have had the opportunity to experience at first hand.

551.553.11:551.515.82

A sea-breeze front seen by radar

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Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

Ahead of a cold front on 7 May 1990, there was an exceptionally distinct sea-breeze over parts of the Swedish east coast. The sea-breeze front was clearly depicted by the Norrköping Doppler weather radar. The echoes, which were weak, did not originate from precipitation, but were clear air echoes from insects or sharp gradients in the refractive index of the air. The operative Doppler weather radars of today are sensitive enough to detect those echoes on practically every day in the warmer seasons (in our climate).

Fig. 1 gives a mesoscale analysis of the wind field at anemometer height. The positions of the sea-breeze front at successive times are also given. Fig. 2 is a pseudo-CAPPI

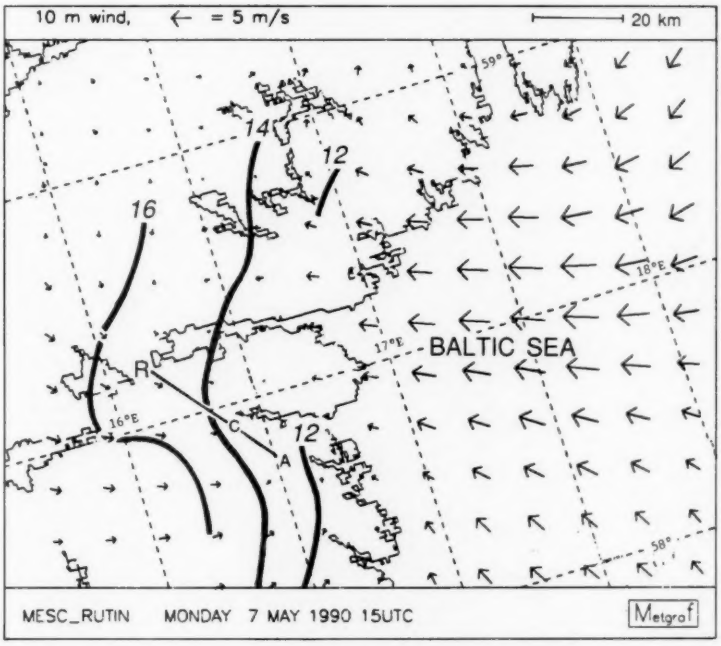

Figure 1. Mesoscale analysis of the wind at anemometer height at 15 UTC on 7 May 1990. Isochrones for the sea-breeze front at 12, 14 and 16 UTC are given. The baseline of the vertical cross-section in Fig. 4 is marked R–A, and R is the position of the radar.

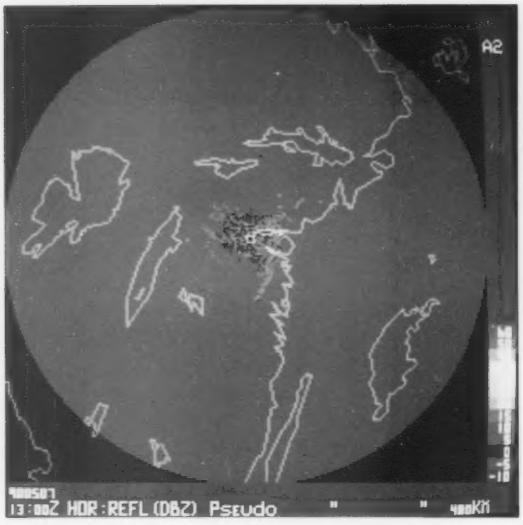

Figure 2. Pseudo-CAPPI of reflectivity at 13 UTC on 7 May 1990. The reflectivity scale is given to the right. The Norrköping Doppler weather radar with a range of 240 km.

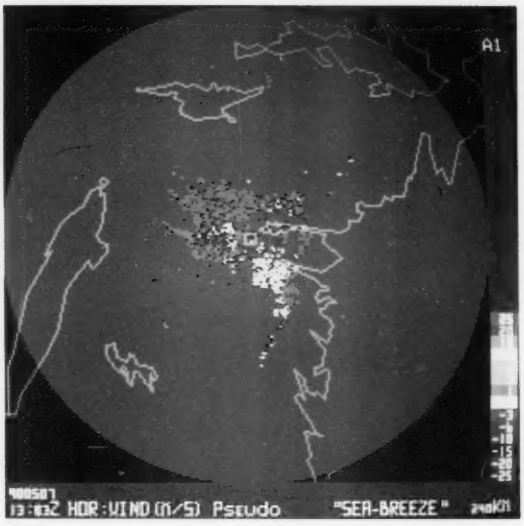

Figure 3. PPI (antenna elevation angle 0.4°) of radial wind at 13 UTC on 7 May 1990. The radial wind scale is given to the right. Positive winds blow out from the Norrköping Doppler weather radar — range 120 km.

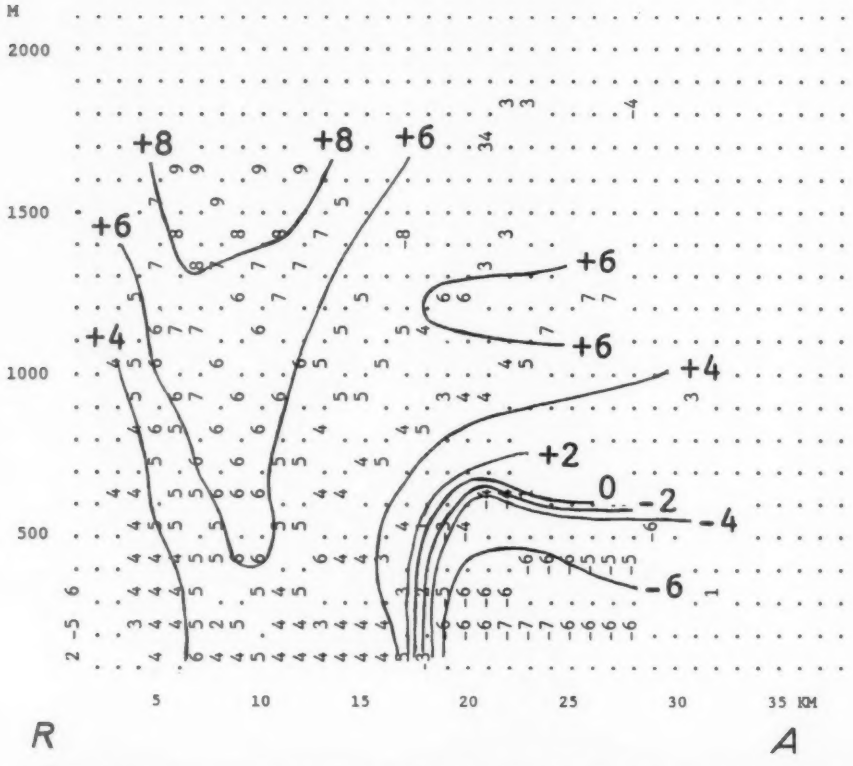

Figure 4. Vertical cross-section of radial winds along the line R–A in Fig. 1 at 14 UTC on 7 May 1990.

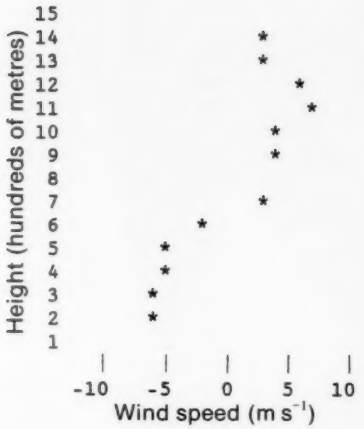

Figure 5. Vertical profile of radial winds at a range of 25 km from the radar, at position C in Fig. 1 at 14 UTC on 7 May 1990.

(Constant Altitude Plan Position Indicators) of reflectivity, where the thin (green) line echo shows the sea-breeze front and the weaker (blue) echoes mostly are other clear-air echoes, which give the radial winds depicted in Fig. 3. The sea-breeze wind shift occurs at the border between the positive (yellow, blowing out from the radar) and negative (green, blowing towards the radar) echoes.

A vertical cross-section in the direction of 140° from the radar lies mainly in, and 180° from, the wind directions and therefore gives a good picture of the real winds. Such a cross-section (along the line R–A in Fig. 1) is given in Fig. 4. The clear-air echoes reached up to about 1600 m, and the winds could thus be depicted up to this altitude. A vertical profile of the radial winds (Fig. 5) at a range of 25 km from the radar in the direction of 140° (at the position marked C in Fig. 1) also shows that this sea-breeze front was very sharp.

Correspondence

Hoar frost deposition

In their useful article about hoar frost deposition on roads (*Meteorol Mag*, **121**, 1–21), T.D. Hewson and N.J. Gait refer to the thickness of hoar frost accumulation that may give rise to a significant ice danger. It seems, however, that they were comparing this with a road surface that would otherwise have been dry. I would suggest that a more appropriate comparison is with a salted road which will rapidly become damp through the hygroscopic effect of the salt. A damp road is not, of course, as slippery as an icy one, but the salty dampness is very much more persistent than early morning hoar frost. In the absence of rain to wash the salt away, the artificial dampening effect can last for many nights and days, mitigated only temporarily each afternoon by partial drying of the salt. The resultant safety penalty from persistent dampness has to be set against any benefit from the original salting.

An informal confirmation can be made by anyone walking to their railway station on a bright winter's morning. The surfaces of roads on the council's salting run can frequently be seen to be damp, or even wet, when unsalted narrow side streets are dry. If, however, the unsalted streets are found to be freshly icy, then there may indeed have been a safety gain from salting, at least as far as that locality was concerned.

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Reviews

The *New Scientist* guide to chaos, edited by N. Hall. 153 mm × 234 mm, pp. 224, *illus.* London, Penguin Books Ltd, 1992. Price £9.99. ISBN 0 14 014571 0.

A year or two ago, a series of articles appeared in New Scientist on chaos theory and its implications for different branches of science. This book, compiled by the physical sciences editor of that journal comprises the complete series and contains contributions from 18 authors mainly from British universities.

The series begins with a historical review following the development of mathematical physics through the deterministic theories of Newton and Laplace, and the quantum theory of the 1920s with its randomness and unpredictability to the new theory of chaos, unpredictable yet deterministic. This is followed by several chapters illustrating the nature of chaos and designed to give the reader a feel for chaotic behaviour.

For a practical example of chaos, a pendulum seems an unlikely candidate but a spherical pendulum under forced oscillation near its resonant frequency readily shows the symptoms. An easily followed mathematical chapter looks at chaos from a theoretical point of view, and an occasionally light-hearted chapter on visualizing chaos introduces trajectories, attractors, bifurcation, etc. and supports the author's assertion that 'a picture is worth a million numbers'.

Fluid dynamics provided some of the earliest recognized physical manifestations of chaos, particularly turbulent flows. It has also proved one of the most difficult to study. A general chapter on fluids uses simple laboratory systems as examples — real turbulent flows are just too complex.

Chaos is a well-known occupational hazard for weather forecasters. Tim Palmer from ECMWF explains how ensemble forecasting (generating several predictions with slightly different initial conditions) provides information on the reliability of forecasts. In the tropics the influence of sea surface temperature anomalies makes things more complicated — reliable extended-range forecasting of El Niño requires a coupled atmosphere–ocean model. All this is explained in a very readable manner without a single equation.

Subsequent chapters show how chaos has influenced research in many other branches of science. Electric circuits, especially those involving feedback or signal amplification, have always relied on the designer's intuition to avoid non-linearity and spurious response, but chaos is helping to replace art by science. In the life sciences, chaos has applications to population dynamics, genetic variability and neurophysiological disorders.

Several authors point out that interest in chaos stems from the limitations of traditional theoretical techniques based on studies of systems in static or dynamic equilibrium. Applied to systems far from equilibrium or with strong transient forcing, the latter not only fall down in their quantitative predictions but sometimes even fail to predict the type of behaviour experienced. Thus ships capsize in heavy seas, structures fail in gusty winds, and thermodynamic and chemical systems evolve in unexpected ways. A chapter on chemistry dwells largely on a laboratory curiosity, the cyclic Belousov–Zhabotinskii reaction, but also mentions combustion and catalysis, both of great importance in industry.

Some applications are more unexpected. Gravitational effects can cause chaotic behaviour in the orbits of asteroids, and even the earth's orbit may be unpredictable on time-scales of hundreds of millions of years. A surprising discovery is that as the size of physical systems are reduced to the point where quantum theory takes over from classical physics, chaotic behaviour is suppressed. On the stock market, prices are controlled by complicated feedback interactions — conditions in which chaos can thrive. However there are so many external random market forces that it is difficult to detect chaotic behaviour in economic data with any confidence.

Two chapters on fractals (one of them by Benoit Mandelbrot) comprise an introduction to the subject, material which will be familiar to many readers. A chapter on number theory, though interesting, seems a little out of place as it says much about randomness but little about chaos.

The variety of scientific disciplines in which the theory of chaos has found application is perhaps the most lasting impression given. Although only the simplest mathematical systems have been studied so far, the common picture of chaos that emerges is one of exponential error growth stemming from non-linearity resulting either from resonance (where amplitude growth is restricted only by non-linear effects) or from feedback mechanisms. A brief summary chapter to point out these common threads through the book would have made a useful conclusion.

The book is well printed and the black and white figures are supplemented by 16 pages of colour plates, mostly computer generated. On the whole, the similar depth of coverage by each author preserves a good balance with a few references for further reading at the end of each chapter. In spite of the variety of authors, a number of chapters contain references to work described elsewhere in the book thus avoiding unnecessary repetition.

It would be interesting to compare the contents of the present book with that of an updated version published in, say, 10 or 20 years' time. Such is the widespread applicability of chaos and the unpredictable nature of its revelations that the future development of the subject may itself provide yet another example of the theory in action. In the meantime, the present book will provide a useful and comprehensive background for understanding the behaviour of our chaotic world.

B.R. Barwell

Plants and Microclimate: A quantitative approach to environmental plant physiology (second edition), by H.G. Jones. 150 mm × 227 mm, pp. xxiv+428, *illus*. Cambridge University Press, 1992. Price, £55.00, $100.00 (hardback, ISBN 0 521 41502 0), £19.95, $39.95 (paperback, ISBN 0 521 42524 7).

This second edition is a thorough review of the first, with all aspects of the book improved or brought up to date. For a review of the first edition, see *Meteorological Magazine*, **114**, 62–63. The basic purpose of the book remains to 'provide a soundly based introduction to those features of the atmospheric environment of relevance to plants', and while the basic structure of the first edition remains, changes have been made to the text, tables, figures, references and the sample questions at the end of each chapter.

The book starts with an introductory chapter on modelling and experimentation which now includes a mention of the practical uses of models as well as their scientific contribution. The following three chapters on the physics of radiation, heat, mass and momentum transfer and also evaporation are revised to include further information on indirect methods for determining canopy structure and evaporation from plant communities.

The remaining chapters are organized much as before except that the old chapter 'Environmental Control of Morphogenesis' has become 'Light and Plant Development'. In these chapters are described topics such as plant-water relations, stomata, photosynthesis and respiration, temperature, drought, the effects of wind and altitude, and with a section on the 'greenhouse effect' and the effects of atmospheric pollutants. New topics include chlorophyll fluorescence, carbon isotope discrimination and high temperature injury.

All of this is presented in a thorough, but easy to read style much of which would be useful to meteorologists faced with trying to understand plant–atmosphere interactions. Chapter 3 now includes transfer processes in the canopy (penetration of gusts) and the evaporation section now has the concept of 'coupling to the environment', both of which topics have appeared in the last 10 years. Chapter 9, on plant development, is timely because of the increasing interest in crop simulation models. However, it would have been useful to have had an example, say the AFRC wheat development model, which demonstrates the use of thermal time modified by both photoperiod and vernalization. The section on water-use efficiency is expanded and there is now a section on the 'Crop Water Stress Index' introduced recently as an aid to irrigation management. The new section on the greenhouse effect forms a useful introduction to the topic and concentrates on the effects of carbon dioxide on plants while rightly drawing attention to the errors in prediction of future climates by global climate models.

The book is over 100 pages longer than the first edition. In part this is due to new additions, but also because it has slightly smaller width and length and a slightly larger print size. It is easier to read than the first edition and the use of a system of bolding text when a definition is first used is a great help. The 'Answers to selected problems' contains brief working as well as the final answer, which can be a help if you are not sure how to tackle a problem. All the symbols are explained in a glossary, but users familiar with the first edition will have to be a bit careful at times because the meaning of some symbols has changed, e.g. 'i' in the first edition meant 'inlet', but this changes to 'e' in the new edition. Some minor errors remain, e.g. in Figure 2.1 the '0' should be '10 to the power 0' and on page 204 '17.5 Kg/g' should be '17.5 KJ/g'. However, these are minor complaints about an excellent revision, although some of the new material would not be of great interest to meteorologists.

M.N. Hough.

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

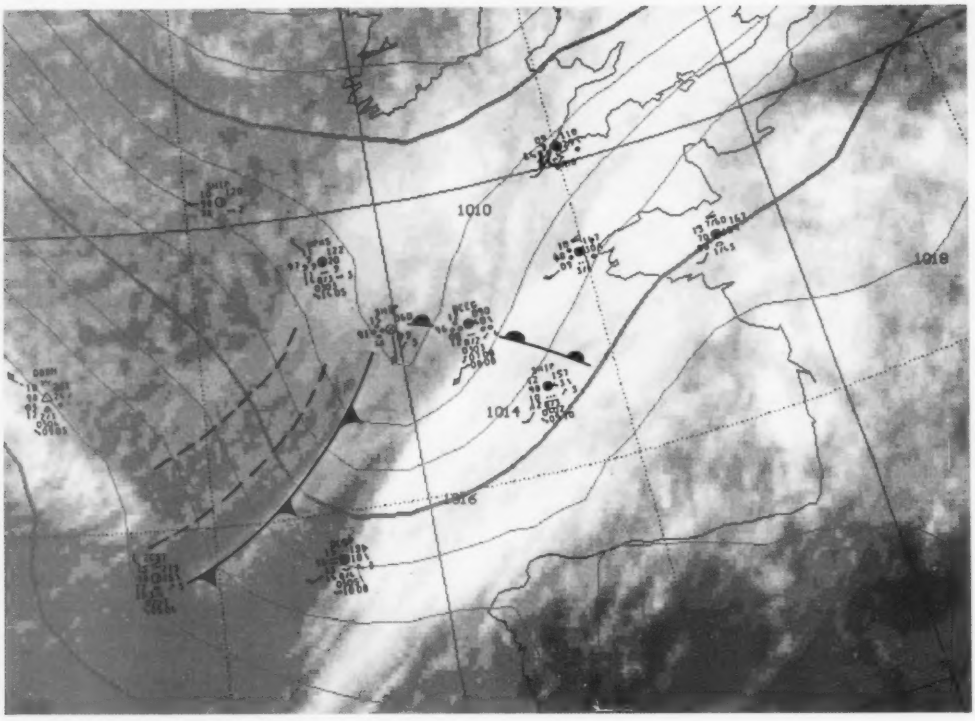
Glaciers, by M. Hambrey and J. Alean (Cambridge University Press, 1992. £19.95, $29.95) contains many photographs (mostly colour) of glaciers and their accoutrements from worldwide locations. The text aims to describe and explain glaciers while conveying their beauty and importance. ISBN 0 521 41915 8.

International weather radar networking, edited by C.G. Collier (Dordrecht, Kluwer Academic Publishers Group, 1992. £66.00, $110.00, Dfl.190.00) contains about 40 papers presented at a COST-73 seminar at Ljubljana in June 1991. The wide-ranging contents highlight the many facets involved in creating and combining national and international networks. ISBN 0 7923 1706 8.

Climate change: Science, impacts and policy, edited by J. Jäger and H.L. Ferguson (Cambridge University Press, 1991. £50.00 (hardback), £24.95 (paperback)) contains the proceedings of the Second World Climate Conference held in Geneva in October–November 1990. The papers included cover all aspects of climate, and the book is material evidence of the remarkable cooperation of six international agencies. ISBN 0 521 41631 0, 0 521 42630 8.

Greenhouse earth, by A. Nilsson (Chichester, New York, Brisbane, Toronto, Singapore, John Wiley and Sons, 1992. £9.95) attempts to 'translate' the scientific community's report on the subject for the non-scientific reader. The variety of scenarios painted, caused by the different factors considered, are described. ISBN 0 471 93628 6.

Infrared image of a cloud-head — 27 April 1992 at 1800 UTC



The figure shows a Meteosat infrared image of a cloud-head (see Monk and Bader*) associated with a developing low. Superimposed on this are isobars at 2 mb intervals taken from the 1800 UTC operational analysis of the Meteorological Office unified limited area model (LAM), together with a selection of surface observations. The low subsequently tracked east-north-east, deepened to about 996 mb by 0600 UTC on the 28th, generated 60 m.p.h. gusts over the Channel Islands, and produced 10–20 mm of rain over southern Britain from the northern portion of the cloud-head (i.e. that centred around 50° N, 09° W at 1800 UTC).

During the period 1230 to 2030 UTC on the 27th, 67 dropsondes were released in the vicinity of the low, from the Met. Research Flight's C-130 aircraft, as part of the 'FRONTS '92' project. Preliminary cross-sections derived from the sonde data have indicated the presence of one surface warm front, and up to four surface cold fronts. The most pronounced cold front crosses 45° N, 14° W. The plotted warm and cold front positions are based partly on this cross-section data, and partly on surface observations.

The figure exhibits the following features:

(a) The warm front is not collocated with any particular feature on the imagery. However, the multiple cold fronts are linked to banding in relatively warm, low cloud. The main band of cirrus (through 45° N, 10° W), which might appear to be frontal, does in fact lie well ahead of the main surface cold front. The C-130, flying at 20 000 ft, traversed a region of clear air below this cirrus.

(b) The heaviest precipitation is generally not coincident with the coldest cloud tops — note the two ship observations closest to 48° N, 09° W. This inference is supported by other ship observations (not shown), as well as data from the aircraft radar. It follows that most of the precipitation is probably being generated in the lower troposphere.

(c) The unified LAM pressure field appears to have underestimated the depth of the low. This is partly due to late ship observations having been missed by the data assimilation, but also emphasizes the importance of hand-drawn analyses. Issued forecasts for this low and the associated weather showed a marked improvement on the model guidance.

T.D. Hewson

* Monk, G.A. and Bader, M.J.; Satellite images showing the development of the storm of 15–16 October 1987. *Weather*, **43**, 1988, 130–135.

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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